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SOLAR VARIABILITY AND TERRESTRIAL WEATHER.(U)
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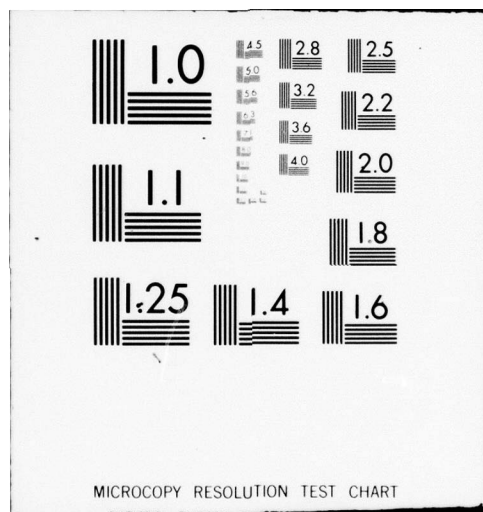
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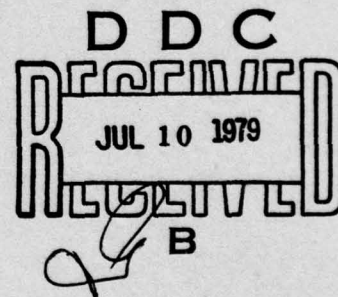
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Philip H. Scherrer

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SOLAR VARIABILITY AND TERRESTRIAL WEATHER

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Introduction

The past four years have seen a growing interest in possible relations between terrestrial weather and solar or solar wind variability. Most of the work in sun-weather (and climate) studies has sought correlations on three time scales: (1) climate changes over hundreds to thousands of years, related to longer term variations in the solar output, (2) climate changes correlated with the 22-year solar cycle, and (3) weather variations on the scale of a few days, in response to transient solar events. While it has not been conclusively shown that there is a sun-weather connection on any of these time scales, in each case there exists enough supporting evidence to suggest that further study is warranted.

The most convincing evidence is that concerning long-term climate changes which could be connected to changes in the solar luminosity below the threshold of all but the most recent observations, but still involving relatively large amounts of solar energy. Short-term weather changes correlated with solar phenomena cannot be explained in this way, since the effect of such transient phenomena on the Sun's energy output

is far too small. There remains, however, the possibility that such phenomena affect some sensitive links in the sun-solar wind-magnetosphere- stratosphere-troposphere causal chain, such that a small variation of the input can trigger relatively large-scale consequences. Most of this review will be concerned with developments in the short-time scale connections.

In sun-weather work, as with most scientific fields, much of the exchange of ideas and results takes place at meetings and symposia. Because of the interdisciplinary and often controversial nature of sun-weather work, such meetings play a rather central role in it. During the past four years many symposia and special sessions devoted to this topic were held in the United States, in addition to several international meetings with important contributions from U.S. authors. Some of these meetings are listed below, with references to published proceedings or summaries where available.

The quadrennium began with a joint meeting of the AAS Solar Physics Division and the AMS in Denver, Colorado in January 1975. This was followed by a symposium on Global Effects of Interplanetary Medium-Magnetospheric- Lower Atmosphere interactions at the IUGG General Assembly in Grenoble, 1975. Next came the International Symposium on Solar-Terrestrial Physics in Boulder (Williams, 1976), the Joint Symposium on Influence of Solar Activity and Geomagnetic Change on Weather and Climate at the IAGA/IAMAP Assembly, Seattle 1977 (Johnson and Belmont, 1978), the Solar Terrestrial Coupling Conference at Yosemite, 1978, and the Symposium/Workshop "Solar-Terrestrial Influences

on Weather and Climate" at the Ohio State University, also in 1978 (McCormac and Seliga, 1979). Sun-weather relationships have also been the topic of Working Group VIII of the US-USSR Agreement on Protection of the Environment with a number of meetings in both countries.

Workers in the field have greatly benefited from Working Documents I and II prepared by Shapley et al. (1975) and Shapley and Kroehl (1977) for the Special Committee on Solar Terrestrial Physics (SCOSTEP) of the IUGG. A number of general reviews of work in the field have been published, including those by Wilcox (1975,1976), Pittock (1978), and Siscoe (1978). There have also appeared a number of reports and collections which provide important background information for continued studies of the sun-climate and weather question, including an excellent examination of the solar output and its variations (White,1977). The many separate contributions to this book describe the solar input to the terrestrial system over the entire spectrum of radiative and particle fluxes for all time scales.

In 1975 the Panel on Climatic Variation of the U. S. Committee for the Global Atmospheric Research Project (GARP), prepared a broad summary of knowledge about climate variations and their causes (NAS,1975). This report provides a basic introduction into the study of climate for the solar and magnetospheric physicist. Mitchell (1976) has reviewed climate variability and its causal mechanisms over the entire range of time scales. He distinguishes between changes depending primarily on internal stochastic processes of the atmosphere and changes due to processes outside the atmospheric system. In the proceedings of a

recent Symposium/Workshop (McCormac and Seliga 1979), Livingston (1979) reviewed the physical origin, spectral nature, energetics and variability of the solar output; Hones (1979) described the influence of the Sun's particulate emissions on the Earth's magnetosphere and ionosphere; Markson (1979) discussed the possible role of atmospheric electricity in providing a mechanism to explain sun-weather correlations; and Roberts (1979) and Wilcox (1979) described the development and present state of sun-weather connections. Herman and Goldberg (1978a) have published a book which should serve both as a comprehensive review and as a handbook of terms and methods for this interdisciplinary field.

Solar Activity and Climate

Eddy (1976) has re-examined the long term variability of the general level of solar activity and has noted that many historical climate records suggest a sun-climate connection. By the use of proxy data for the level of solar activity, primarily the $^{14}\text{C}:^{12}\text{C}$ ratio in tree rings controlled by the solar modulation of galactic cosmic rays, a tentative record of the average level of solar activity has been extended from recent historic times to 7500 years b.p. (Eddy, 1977). Figure 1 shows the reconstructed solar activity index (curves a,b) compared with four measures of climate (curves c): The long-term correlation of solar activity and climate is clearly evident. Eddy has used the solar wind modulation of cosmic rays to measure solar activity and he has suggested the Sun-climate correlation may be due to a slow modulation in the

"solar constant", of the order of 1%, in phase with the mean level of solar activity. Alternative explanations are that variations in solar UV radiation or cosmic ray modulation of stratospheric chemical processes may be the source of such climate variations (e.g. Chamberlain, 1977). As a result of these and other studies, the solar-climate connection on the long time scale seems well established.

In order to assess the reality of suggested sun-climate correlations accurate information about variations in the solar constant and the effects of such variation on climate is needed. Schneider (1977) has briefly described the sensitivity of the climate system to solar constant variations (see also Schneider and Mass, 1975). He concluded that a global surface temperature change of 1K could result from a change in the solar irradiance of from 0.2% to 2% depending on the model and assumptions used.

Several authors have suggested a correlation between solar activity and the solar constant. There is at this time no confirmed observation of a systematic variation of the solar constant. Direct long term observations since about 1900 show that any variation on that time scale was less than 1%. Several recent high altitude studies with accuracies near 0.2% have not been able to exclude the possibility of a variation with the sunspot cycle (Frohlick, 1977). More recent observations from rockets and spacecraft (Duncan, 1979) suggest that there may be an increase of a few tenths of a percent since sunspot minimum. In order to unambiguously answer these questions, frequent observations must be made with accuracies better than 0.1% over the next decade or so.

Pittock (1977) has recently critically examined reported correlations between the 22-year solar cycle (and its 11-year harmonic) and found that most claims have a poor statistical basis at best. However, one set of correlations on this time scale has so far survived close scrutiny and is accepted by many investigators as "real". This is the work of Mitchell and Stockton (1979) on the relationship between drought occurrence areas in the western U.S. and the 22-year solar magnetic cycle. Previous work (reviewed by Roberts, 1973) which relied on historical records of drought occurrence in the high plains states of the western U.S. showed evidence for a connection between the solar cycle and droughts. However, due to the short time span of recorded climate data the correlation remained uncertain. Mitchell and Stockton (1979) have used tree-ring measurements as proxy data to extend knowledge of the duration and areas of droughts through about 360 years. Using this data to construct a drought area index they found an increased chance of rainfall deficiency in an above average number of regions in the western U.S. during the period of several years near the start of each 22-year solar cycle.

Atmospheric Electricity and Chemistry

The chemical or electrical processes in the atmosphere may be an essential part of the causal chain for sun-weather connections. A number of authors including Ruderman and Chamberlain (1975), Ruderman et al. (1976), Chamberlain (1977), Heath et al. (1975,1977) and Keating (1978) have discussed solar modulation of ozone by UV, particle flux, or

cosmic ray variations. Most of the studies have been concerned with 11-year modulation but Keating found an apparent monthly time scale variation of ozone. More studies along these lines can be expected to yield a better understanding of possible mechanisms as atmospheric models and data improve.

Possible solar flare or interplanetary sector boundary modulation of the Earth's fair weather electric field has been discussed by Park (1976) and by Reiter (1977). These studies reached different conclusions about the sense of such variations but since they were concerned with quite different environments (Antarctica and Europe), it is not clear whether there exists a discrepancy or not. Herman and Goldberg (1978b) have suggested a connection between solar activity and the initiation of non-tropical thunderstorms. Markson (1978,1979) reviewed the question of links between solar activity, atmospheric electricity and weather and found that "the argument that solar modulation of atmospheric conductivity would change the Earth's electric field (is) on firm ground but the possibility of variable solar activity modulating thunderstorm activity, which in turn influences other parts of meteorology, is speculative and awaits further investigation."

Vorticity Area Index

Much of the current interest in sun-weather connections began with the reports of a characteristic change in the size of tropospheric regions of high vorticity in the northern hemisphere near the times of

sharp rises in the geomagnetic Ap index (Roberts and Olson, 1973a,b) and near the times when the earth crossed interplanetary magnetic field sector boundaries (Wilcox et al., 1973, 1974). The principal result from the work of Wilcox et al. is shown in Figure 2. The vorticity area index (VAI) used in that work was originally computed by Roberts and Olson for individual low pressure troughs in the Gulf of Alaska. For the studies using sector boundaries (SBs), the VAI was summed over all latitudes north of 20N. The SBs used were those in the winter months November through March for the years 1964-1970. This work was extended by examining the dependence of the correlation on height in the atmosphere (Svalgaard, 1974), on season (Wilcox et al., 1975), and on latitude (Wilcox et al., 1976). In the latter studies the analysis was extended to the years 1963-1973, raising the total of key dates from 54 to 133. The conclusion of the additional studies was that there exists a persistent hemispheric response of the tropospheric vorticity to the sector structure.

Shapiro (1976) and Hines and Halevy (1975, 1977) have examined the statistical significance of this result. Their conclusion was that for the winter season used by Wilcox et al. (1975) the effect had less than 1 chance in 20 of being due to chance. Hines and Halevy concluded, after a thorough study of the statistical properties of the data that the result appeared to be statistically significant and that a search for the physical cause was justified. They also found that the effect could be explained if solar modulation was able to shift slightly the timing of natural meteorological variations, a process by which a

relatively small energy input (like that available in short-term solar events) can influence much more energetic processes in the lower atmosphere.

In a different search for short-term sun-weather connections, Bhatnagar and Jakobsson (1978) found no sector boundary related response in hemispheric average kinetic energy or mean square vorticity. This work was examined by Larsen (1978) who pointed out that the parameters investigated by Bhatnagar and Jakobsson would be insensitive to the variation in VAI that Wilcox et al. found. Williams (1978) also investigated the energetics in the atmosphere for correlations with SBs. He examined separately zonal available potential, eddy available potential, zonal kinetic, and eddy kinetic energy parameters for winter and summer seasons. While not as statistically significant as the VAI effect, he found some resemblance between the signature from Figure 2 and corresponding variations of the wintertime eddy kinetic energy parameter. This effect was stronger for the first half of the interval (1963-1969) than for the latter half (1969-1976).

Using a different data set (Limited Fine Mesh grid covering North America) Larsen and Kelley (1977) examined the VAI effect for the years 1972-1974 and found the same 10% dip in VAI as was found in earlier work. They also examined the vorticity maps produced by one of the National Weather Service's prognostic models and found a decrease in the accuracy of the forecast for the time corresponding to the dip in VAI (Figure 3). This result is one of the first in which the sun-weather effect has a potential practical significance, in addition to the

statistical and physical significance.

Many tentative sun-weather correlations, proposed on the basis of limited study periods, have been abandoned after additional data failed to support the initial hypothesis. It was to a large extent the stability of the VAI effect when the SB list was extended from 54 to 133 key times that convinced Hines and Halevy that the effect warranted further study. Following the observations of Williams (1978) that the eddy kinetic energy showed a larger response for the years before 1969 than for 1969-1976, Williams and Gerety (1978) examined the VAI response for the years 1974-1977. They found a similiarly shaped but probably not statistically significant response for the 300mb VAI and essentially no response at 500mb. Although Williams and Gerety noted "...the simplest interpretation is that the years 1963-1973 yielded an anomalous result which was of unusually high statistical significance and which was self consistent for an unusually long time," they also suggested that it is necessary to examine possible changes in the physical conditions on the sun, in the solar wind, and in the atmosphere which may altered a real sun-weather connection.

Wilcox and Scherrer (1979) did investigate year-to-year changes in the VAI and found that the sun-weather effect may actually be rather constant for the years 1963-1978. They first confirmed the observation of Hines and Halevy(1975,1977) that the size of the VAI response is larger when the variance of the VAI is larger. It was found that for the group of SBs associated with larger VAI variance, the size of the VAI response was rather constant for 1963-1978. For the SBs associated

with smaller VAI variance there was essentially no response. In the last few winters the VAI mean value and variance have decreased thus the number of SBs associated with larger variance has decreased. This change in the VAI apparently explains the null result found by Williams and Gerety (1978). While the change in the VAI in recent years may be the cause of the diminished effect when all SBs are used, the reason for the lack of an effect prior to 1962 (Wilcox and Scherrer, 1979) has not been fully studied and may be due to several factors including a lower level of VAI mean value, VAI variance, the poorer timing accuracy of inferred as compared to spacecraft observed SBs, some other difference in solar or atmospheric conditions or to the absence of a sun-weather connection. These questions probably will not be satisfactorily answered until we are several years into the present solar cycle and have several additional years of spacecraft determined SBs.

Further Sun-Weather Studies

Along the lines of earlier work, Olson et al. (1975, 1978) have examined changes in VAI correlated with major events of solar activity. They have found VAI increases followed by decreases, in a form suggesting a solar activity - sector structure - geomagnetic activity - VAI variation chain. Wilcox et al. (1979) have used the original data of Roberts and Olson (1973a) for individual trough areas and found a correlation depending on the polarity (toward or away from the sun) of the interplanetary magnetic field at the time when the trough was in the Gulf of Alaska. While these studies and the VAI vs SBs effect do not

yet merge to form a unified picture of a sun-weather response, they may do so in time.

Shapiro and Stolov (1978) examined skill scores of the National Meteorological Center atmosphere model and found no appreciable change in forecast skill near the times of SBs or geomagnetic disturbed or quiet days. This may not be too surprising since the index used is sensitive to changes in the entire atmosphere as was the case for the null result of Bhatnagar and Jakobsson(1978). It is interesting to note that most investigations which have found a significant correlation between a solar quantity and an atmospheric index have used an index which is a measure of the area of extremes of weather conditions rather than the actual value of an atmospheric index.

In conclusion, it can be said that the past four years have been very active for sun-weather research in the U.S. Some quite specific questions have been posed by recent work: the time variation of the VAI vs SB effect, the nature of the clear-air electric field and the relationship of the ionospheric potential to thunderstorm formation, and the constancy of the solar "constant" both in terms of the total luminosity on the climatic time scale and for near UV radiation on the time scale of days to 11 years.

No doubt, the existence of short time sun-weather connections will still be a controversial topic four years from now. One can hope though, that continued research will help to at least solve the problems mentioned above and will resolve in one way or the other the major questions raised by work in the past four years.

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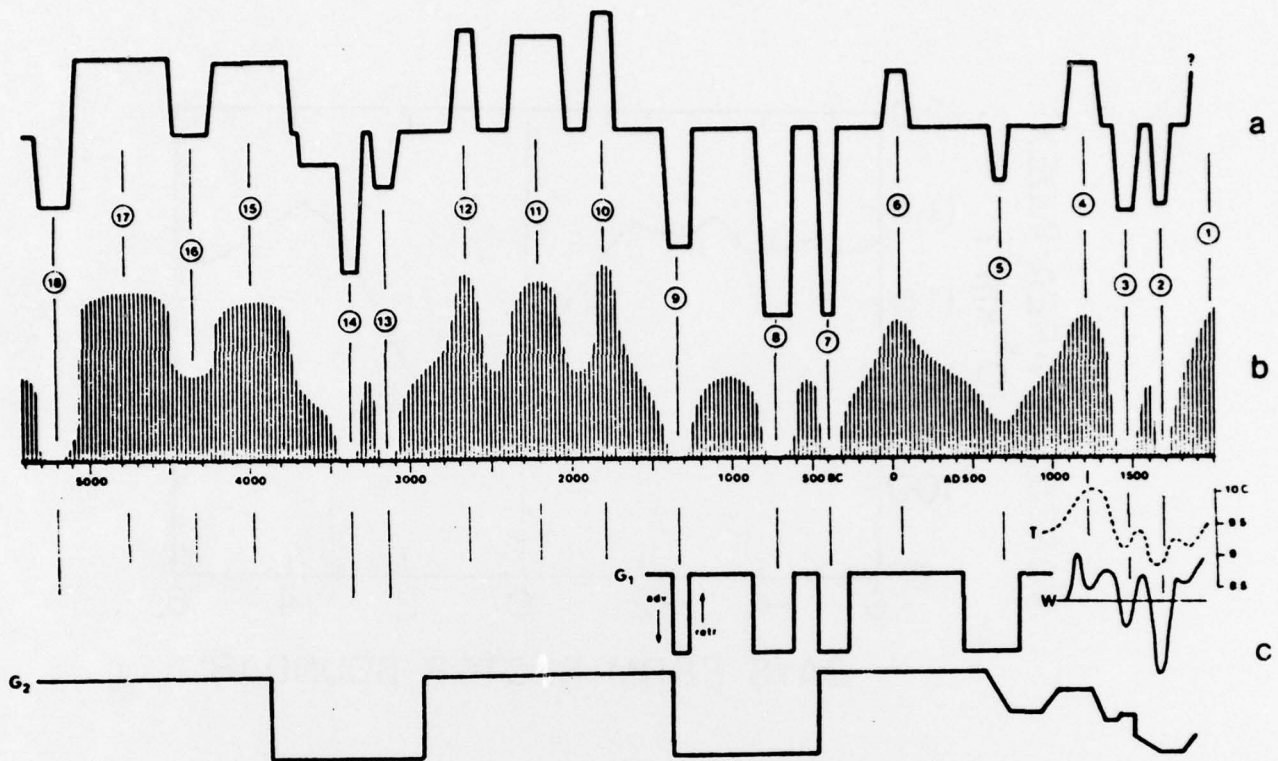


Fig. 1. Curve a shows persistent deviations in ^{14}C plotted schematically and normalized to the Maunder minimum (feature 2). Downward excursions refer to increased relative ^{14}C and imply decreased solar activity. Curve b is an interpretation of curve a as the long-term envelope of solar activity. Curves c are four estimates of past climate as measured by glacial advance and retreat times (G_1 and G_2), England mean annual temperature (T), and Paris-London area winter severity index (C). From Eddy (1977).

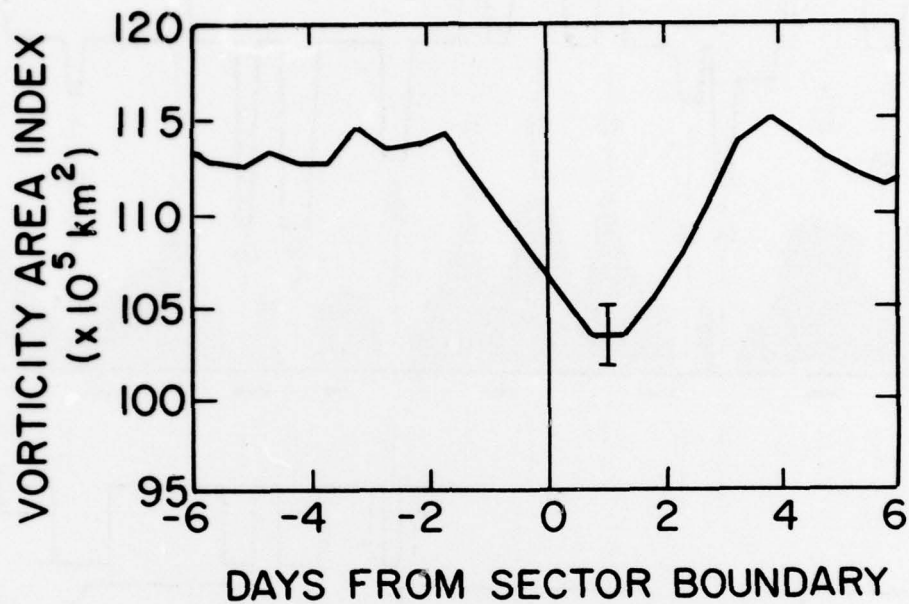


Fig. 2. Average response of the vorticity area index to the solar magnetic sector structure. The sector boundaries were carried past the Earth by the solar wind on day 0. The vorticity area index is the area in the northern hemisphere where the vorticity exceeded $20 \times 10^{-5} \text{ s}^{-1}$ plus the area where it exceeded $24 \times 10^{-5} \text{ s}^{-1}$ (Wilcox et al., 1974).

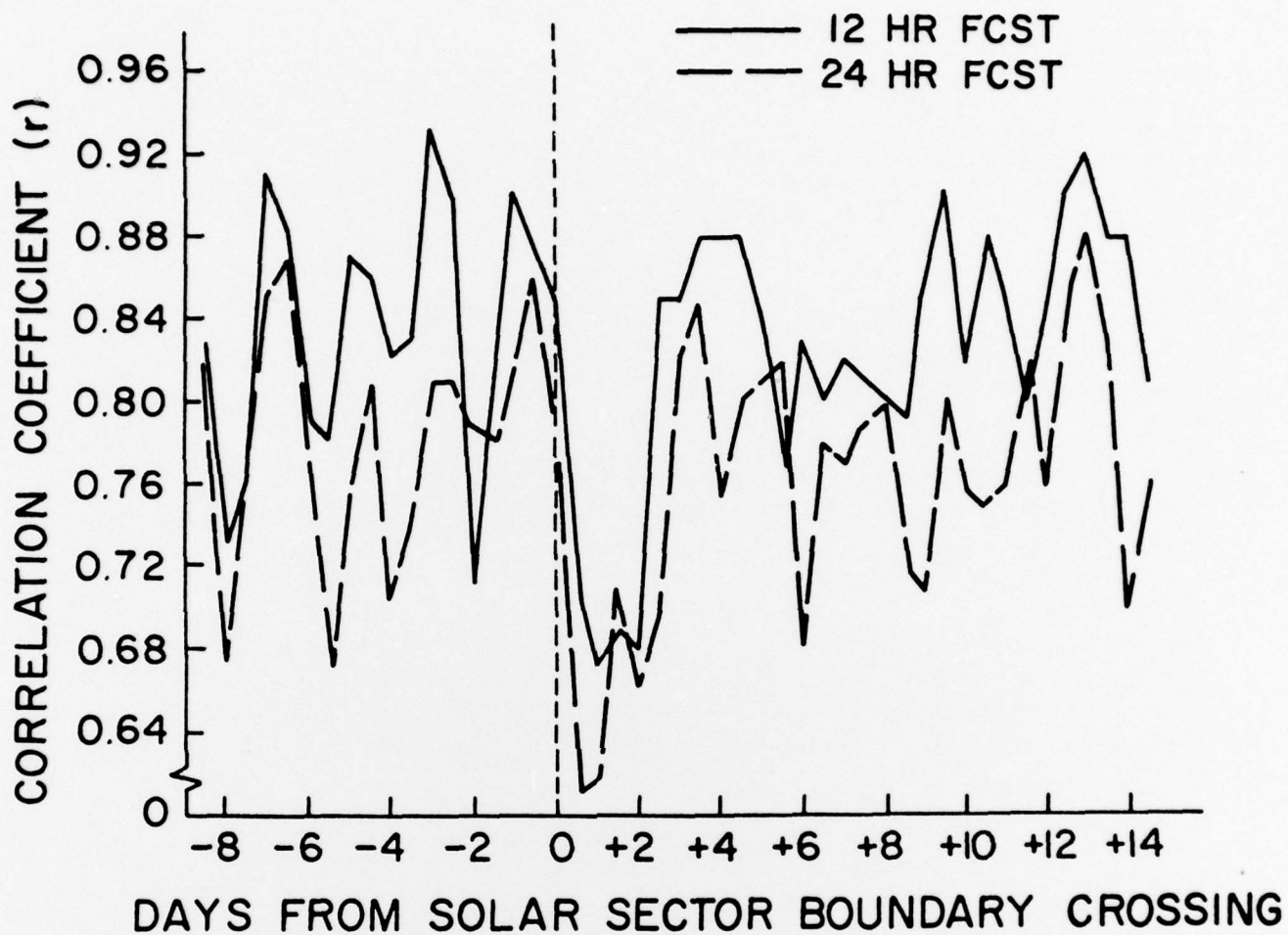


Fig. 3. An analysis of the accuracy of forecasts of tropospheric vorticity near the times of sector boundary passages. The ordinate is a cross correlation between the forecast and observed vorticity area indices. During the first two days after the boundary the correlation coefficient appears to be systematically lower by about 0.15 units (Larsen and Kelley, 1977).

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